

# Measurements of the Čerenkov light emitted by a $\text{TeO}_2$ crystal

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**ABSTRACT:** Bolometers have proven to be good instruments to search for rare processes because of their excellent energy resolution and their extremely low intrinsic background. In this kind of detectors, the capability of discriminating alpha particles from electrons represents an important aspect for the background reduction. One possibility for obtaining such a discrimination is provided by the detection of the Čerenkov light which, at the low energies of the natural radioactivity, is only emitted by electrons.

In this paper, the results of the analysis of the light emitted by a  $\text{TeO}_2$  crystal at room temperature when transversed by a cosmic ray are reported. Light is promptly emitted after the particle crossing and a clear evidence of its directionality is also found.

These results represent a strong indication that Čerenkov light is the main, if not even the only, component of the light signal in a  $\text{TeO}_2$  crystal. They open the possibility to make large improvements in the performance of experiments based on this kind of materials.

**KEYWORDS:** Bolometers; Čerenkov light.

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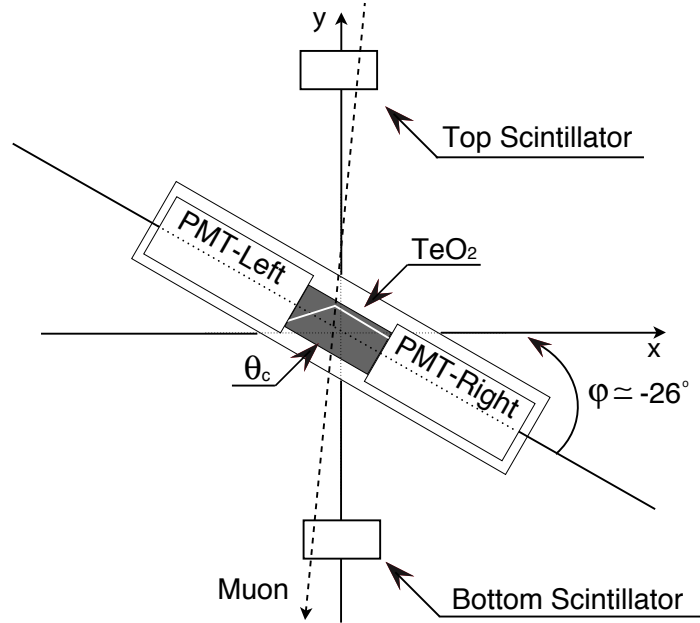
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## 1. Introduction

Tellurium dioxide ( $\text{TeO}_2$ ) crystals have proven to be superb bolometers for the search of neutrinoless double beta decay [1, 2]. They are able to measure energies in the MeV region with a resolution of the order of few keV. One of the main sources of background in these searches is represented by the  $\alpha$  particles emitted by natural radioactivity. As predicted in [3] and demonstrated in [4], the observation of light emitted by electrons in a  $\text{TeO}_2$  bolometer can provide a powerful tool to disentangle  $\alpha$  from  $\beta/\gamma$  radiation. According to their results, the detected light was compatible with the Čerenkov emission, even though the scintillation hypothesis could not be discarded. The aim of the experiment presented in this paper is the assessment and the measurement of the Čerenkov contribution in the light yield of a  $\text{TeO}_2$  crystal. In order to distinguish it from a possible scintillation emission, the differences between these two processes can be exploited. The scintillation light is isotropically emitted and usually shows a time development with an exponential decay typical of the material. Čerenkov light is instead promptly emitted when a charged particle crosses a material with a velocity larger than the speed of light in that material. Moreover, Čerenkov photons are emitted in a cone with an opening angle  $\theta_c = \arccos(1/(\beta n))$  with respect to the particle direction. As it was already demonstrated [5]-[8], the study of the signal shape and of the directionality of the light yield represents an useful tool to disentangle these two components.

## 2. Experimental set-up

To perform the measurements of the light produced by a  $\text{TeO}_2$  crystal, the set-up shown in Fig. 1 was built. A  $5 \times 2.5 \times 2.5 \text{ cm}^3$  crystal placed inside a black box was read-out on the two small opposite faces with two photomultiplier tubes (PMTs) XP2970<sup>1</sup>. These tubes were chosen for their extended sensitivity in the UV region where the production of Čerenkov photons is expected to be large. They were operated at a voltage of 1200 V, with an expected gain of about  $10^7$ . Their analog signals were sent to a CAEN V1371 8-bit digitizer working with 1 GS/s sampling rate.



**Figure 1.** Experimental setup. See text for details.

The box was free to rotate in the  $XY$  plane giving the possibility of changing the angle  $\varphi$  between the longest crystal axis and the horizontal direction in the range  $\pm 40^\circ$ . The maximum Čerenkov light transmission to a PMT is expected with the crystal parallel to the Čerenkov photon direction. For an angle  $\varphi_m = 90^\circ - \theta_c = 26^\circ$ , PMT-Left is expected to see the maximum amount of Čerenkov light which, instead, reaches PMT-Right for  $\varphi = -26^\circ$ . In order to select vertical muons in cosmic rays, the trigger signal to the data acquisition, was provided by the coincidence of two 2 cm thick,  $4 \times 7 \text{ cm}^2$  scintillator fingers placed above and below the crystal. The distance between the scintillators was of about 50 cm and the trigger rate was about 0.1 Hz.

## 3. Crystal light yield

The light exiting from a face of the crystal can be separated into two components:

- **A:** a part that is independent from the angle between the muon and the crystal. This light can be scintillation light or Čerenkov light diffused by the internal reflections on the crystal faces losing its initial directionality.

<sup>1</sup> 10-stages, UV-Sensitive, 29 mm diameter. For more information <http://www.photonis.com/en/ism.php>

- $B(\varphi)$ : a component produced with a directionality and for which the probability of exiting from a face of the crystal is a function of the angle  $\varphi$ . This component is expected to be entirely due to the Čerenkov light.

The total light yield on the two lateral faces of the crystal will result:

$$\bar{L}(\varphi) = \frac{\alpha}{\cos\varphi} (A_L + B_L(\varphi)) \quad (3.1)$$

$$\bar{R}(\varphi) = \frac{\beta}{\cos\varphi} (A_R + B_R(\varphi)) \quad (3.2)$$

with  $\alpha$  and  $\beta$  being two parameters that take into account possible non-equalizations of the PMT responses while  $1/\cos\varphi$  is proportional to the path length of the muon within the crystal. Because of symmetry reasons, one expects:

$$A_L = A_R = A \quad (3.3)$$

$$B_L(\varphi) = B_R(-\varphi) = B(\varphi) \quad (3.4)$$

For  $\varphi = 0$  it follows:

$$\bar{L}(0) = \alpha (A + B(0)) = \alpha k \quad (3.5)$$

$$\bar{R}(0) = \beta (A + B(0)) = \beta k \quad (3.6)$$

Defining  $L(\varphi)$  and  $R(\varphi)$  as the responses equalized at  $\varphi = 0$ , it follows:

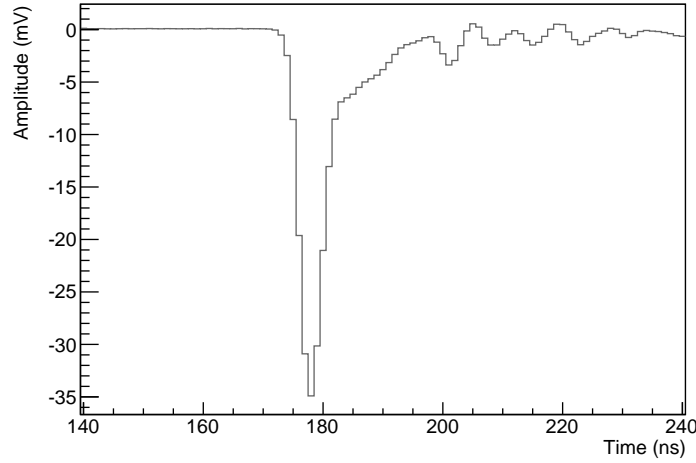
$$L(\varphi) = \frac{\bar{L}(\varphi)\cos\varphi}{\bar{L}(0)} = \frac{1}{k} (A + B(\varphi)) \quad (3.7)$$

$$R(\varphi) = \frac{\bar{R}(\varphi)\cos\varphi}{\bar{R}(0)} = \frac{1}{k} (A + B(-\varphi)). \quad (3.8)$$

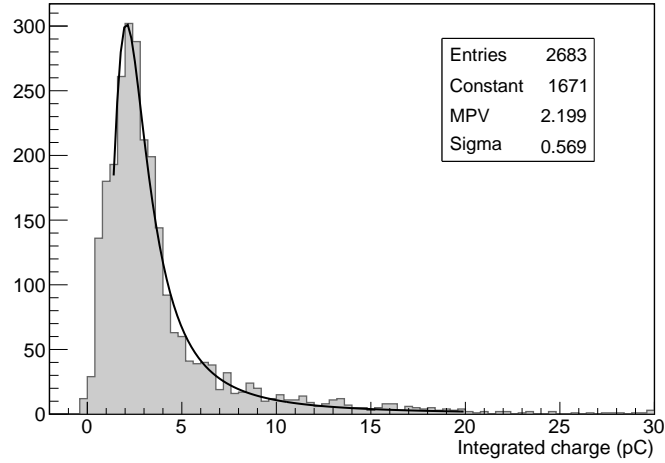
#### 4. Waveform analysis

The waveforms of the signals provided by the two PMTs are acquired and off-line analyzed. The average waveform of PMT-Left obtained for a thousand muon events is shown in Fig. 2. The signals show a rise time and a decay time of the order of few nanoseconds. This very fast behavior is a first indication that an important component of the light is due to Čerenkov emission.

In order to evaluate the charge produced by the PMT, the waveforms are integrated, event by event, in a 15 ns wide time window around the maximum signal amplitude. An example of a charge spectrum obtained by the PMT-Right is shown in Fig. 3. The fit of the charge spectrum with a Landau function returns the average charge and thus an evaluation of the light yield. The effect of the electronics noise is computed by integrating the same waveforms in a 15 ns time interval before the signal pulse. The width of the pedestals resulted to be 20% of the sigma of the Landau distribution. Therefore, the effect of the electronics noise is negligible.



**Figure 2.** Average signal shape of PMT-Left.

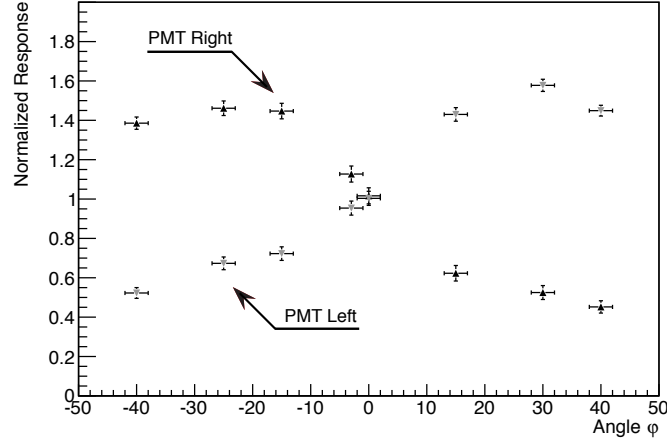


**Figure 3.** Example of the charge spectrum.

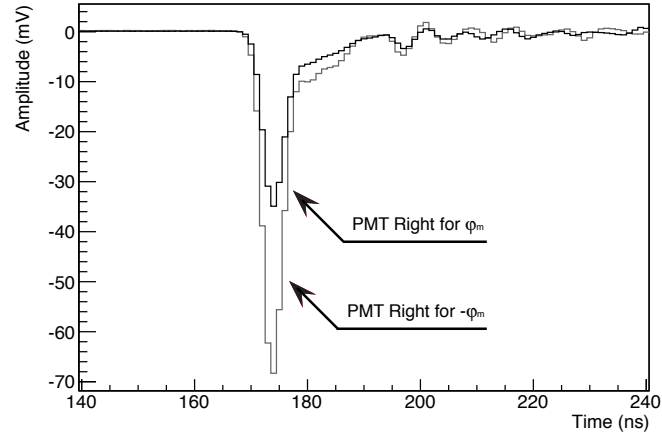
## 5. Results from the angular scan

The dependence of  $L(\varphi)$  and  $R(\varphi)$  on the angle  $\varphi$  are shown in Fig. 4. The two sides show the same behavior. Let's analyse the case of PMT-Left. The light yield, corrected for the path length of the muon within the crystal, is small and weakly dependent on the angle for  $\varphi$  far from  $\varphi_m$ . It shows a marked increase as long as  $\varphi$  approaches the value of  $\varphi_m$  where the transmission of the Čerenkov light is expected to have a maximum. At angles much larger than  $\varphi_m$  a decrease of the amount of light is also visible. A symmetric analysis applies to PMT-Right. This dependence on  $\varphi$  of the signals on the two sides of the crystal is a clear indication that a good fraction of the light is due to Čerenkov photons.

In order to understand the nature of the flat component, the average waveforms of PMT-Right obtained for  $\varphi = \varphi_m$  and  $\varphi = -\varphi_m$  are reported in Fig. 5.



**Figure 4.** Behavior of the responses corrected for the muon path length.

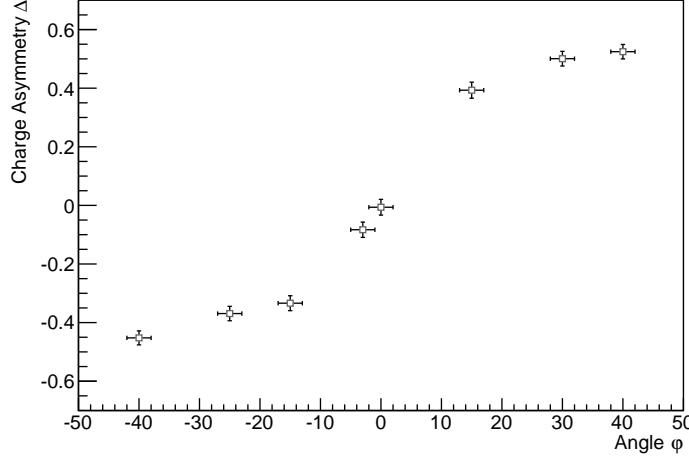


**Figure 5.** Comparison between the average waveforms of the signals provided by PMT-Right as obtained for  $\varphi = \varphi_m$  and  $\varphi = -\varphi_m$ .

Although the amplitudes are different, the signal shapes are the same. In particular, even for  $\varphi = \varphi_m$ , where Čerenkov photons cannot directly reach PMT-Right, the signal is very fast and does not show any slow or exponential tail. This indicates that also the flat component is likely due to Čerenkov light able to reach the PMTs by means of internal diffusion.

## 6. The charge asymmetry

In order to evaluate the ratio between the isotropic component of the light yield and the one that



**Figure 6.** Behavior of the charge asymmetry  $\Delta$  as a function of the angle  $\varphi$ .

depends on  $\varphi$ , the *charge asymmetry*  $\Delta(\varphi)$  is studied. It is defined as:

$$\Delta(\varphi) = \frac{L(\varphi) - R(\varphi)}{L(\varphi) + R(\varphi)} = \frac{B(\varphi) - B(-\varphi)}{2A + B(\varphi) + B(-\varphi)} \quad (6.1)$$

and its behavior is shown in Fig. 6. For  $\varphi \simeq \varphi_m$  the angle-dependent light yield reaches its maximum ( $B_{max}$ ) and, on the other hand,  $B(-\varphi_m) = 0$ . Therefore:

$$\Delta(\pm\varphi_m) = \pm \frac{B_{max}}{2A + B_{max}} \quad (6.2)$$

From the analysis of the data shown in Fig. 6 it results that  $\Delta(-\varphi_m) \simeq -0.45$  and  $\Delta(\varphi_m) \simeq 0.55$  that means two values for  $A$ :  $0.41 B_{max}$  and  $0.61 B_{max}$ . According to the average of our measurements, the ratio between the component of the light yield that depends on the angle  $\varphi$  and the total one is 0.66. This value represents a lower limit of the Čerenkov component value that, thus, results to be at least the 66% of the total light yield.

## 7. Conclusion

The performed measurements show that a  $\text{TeO}_2$  crystal emits light when crossed by a charged particle. The signals are very fast, having a rise time and decay time of the order of few nanoseconds. The amount of light exiting from the crystal has a clear dependence on the angle  $\varphi$  between the particle and the crystal. The maximum of the light is collected for a value of  $\varphi$  compatible with the one expected to maximize Čerenkov light output ( $\varphi_m$ ). A three times smaller amount of light is also detected for angles far from  $\varphi_m$ . Most likely this is Čerenkov light diffused by the crystal lateral faces. However, the measurements reported in the present paper allow to conclude that Čerenkov light represents at least the 66% of all the light emitted by a  $\text{TeO}_2$  crystal.

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